TIME–DEPENDENT HYPERCRITICAL ACCRETION ONTO BLACK HOLES

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Results are presented from a time–dependent, numerical investigation of super-Eddington spherical accretion onto black holes with different initial conditions. We have studied the stability of stationary solutions, the non–linear evolution of shocked models and the time–dependent accretion from an expanding medium.

1 Introduction

Stationary spherical accretion onto black holes is certainly a well–known and extensively studied topic (for a comprehensive review see Nobili, Turolla and Zampieri [1], Zampieri, Miller and Turolla [2]). Up to now all time–dependent investigations of spherical accretion have been concerned either with the analysis of the stability of isothermal [3], isentropic [4] and optically thick[5, 6] flows or with the definition of the parameter space within which high temperature solutions might exist [7, 8, 9]. Very recently, Colpi, Shapiro and Wasserman [10] have studied time–dependent hypercritical accretion of an initially expanding medium to describe the late fall–back of material onto the compact remnant after supernova explosion.

Despite the fact that spherical accretion has been extensively investigated, mainly for shedding light on the efficiency of the radiation generation, several aspects require further consideration such as, for instance, investigating the stability properties of high temperature solutions and searching for the existence and non–linear evolution of possible heated or shocked models. The results of this calculation will be presented in Sec. 2. This study will serve also as a starting point for the investigation of very interesting astrophysical problems, such as the late fall–back of material onto a supernova remnant. A preliminary analysis of this problem will be presented in Sec. 3.

2 Stability of stationary solutions and evolution of shocked models

We have studied the evolution of a self–gravitating, perfect hydrogen gas in the gravitational field of a non–magnetized, non–rotating black hole within the framework of time–dependent radiation hydrodynamics. The present investigation has been carried out by means of a general relativistic treatment of the

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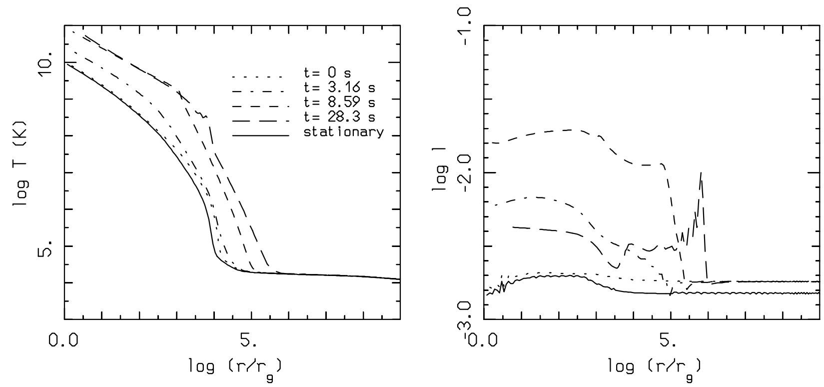

Figure 1: The gas temperature T and the radiative luminosity l (in Eddington units) are plotted versus $\log(r/r_g)$ (r_g is the gravitational radius) at different times for a HL model with initial $\dot{m} = 28.3$ (in Eddington units).

radiative transfer equation, which exploits the expansion of the specific intensity of the radiation field into moments [11]. A detailed review of the derivation of the fundamental equations is presented in Zampieri, Miller and Turolla [2]. The complete system of time–dependent, radiation hydrodynamics equations plus the Einstein Field Equations has been solved using an original numerical method, based on a Lagrangian finite difference scheme [2].

Depending on the physical conditions in the accretion flow, stationary solutions of hypercritical spherical accretion onto black holes show very different behaviours [1]. In the LL (Low Luminosity) models, the inner region of the accretion flow is in LTE with radiation at a low temperature ($T \simeq 10^5$–$10^6 K$) and luminosity and efficiency turn out to be very small ($L \lesssim 4 \times 10^{33}$ erg s^{-1}, $e \lesssim 10^{-7}$). The HL (High Luminosity) models are characterized by very high inner temperatures ($T \sim 10^9$–10^{10} K). In the intermediate region (10^3–$10^5 r_g$, where r_g is the gravitational radius), Compton cooling and free–free emission nearly balance Compton heating, producing a total luminosity 2–3 orders of magnitude larger than that emitted by LL models with the same density.

The time–dependent analysis of LL models shows that they are stable to both thermal and radiative perturbations [2]. Much more spectacular is the phenomenology shown by HL models [2]. At high accretion rates ($\dot{m} \gtrsim 10$, $\dot{m}$ in Eddington units), a thermal instability appears around $10^3 r_g$ after about 2–3 s, as can be seen from Fig. 1, and the temperature increases by almost an order of magnitude. This instability is due to the fact that the radiative heating rate is greater than the radiative cooling rate and, at the same time, the heating time is shorter than the dynamical time. A few seconds after this, the velocity profile starts to deviate significantly from free–fall owing to the large drag exerted by the internal pressure gradients. A compression wave develops, which becomes progressively steeper as it propagates outward and, after 8–10 s,

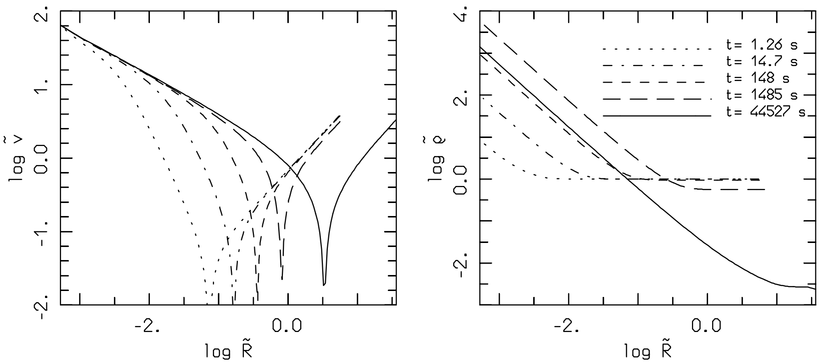

Figure 2: The gas velocity $\widetilde{v}$ (in units of c_s^0) and the gas density $\widetilde{\rho}$ (in units of ρ_0) are plotted versus $\log \widetilde{R}$ ($\widetilde{R} = r/r_a^0$, r_a^0 is the initial accretion radius) at different times. Initial data refer to SN 1987A: $\rho_0 \simeq 10^{-3}$ g cm^{-3}, $c_s^0 = 350$ Km s^{-1}, $r_a^0 = 1.6 \times 10^{11}$ cm.

a hydrodynamic shock forms. The luminosity profile has the typical behaviour shown in Fig. 1 with the long–dashed line, showing a significant initial transient increase lasting ~ 8 s. The shock front moves outward at an approximate speed of 10^8 cm/s $\simeq 10^{-2}c$. Hence this solution is definitely non–stationary.

HL models with low accretion rates ($\dot{m} < 10$) do not show any thermal instability on comparable evolutionary timescales. Having lower densities, the radiative heating and cooling are comparatively less efficient than compressional heating and the gas is essentially adiabatic up to large radii.

3 Spherical accretion from a uniformly expanding medium

After (Type II) supernova explosion of a high mass star, a reverse shock may arise from the collision of the outflowing gas with a sufficiently massive outer stellar envelope, leading to the formation of a dense, expanding flow sorrounding the compact remnant. Models for SN 1987A show that the core density is roughly uniform ($\rho \sim 10^{-3}$ g cm^{-3}) and that the initial velocity $v \propto r$ with a maximum value ~ 2000 Km s^{-1}. After the expansion phase, gravitationally bound shells can accrete onto the compact remnant at hypercritical rates. Colpi, Shapiro and Wasserman [10] found that the total accreted mass is $\sim 0.1 M_\odot$ and could suffice to drive a remnant borne as a neutron star to further collapse to a black hole for a relatively soft equation of state. In this respect we note that, for the large accretion rates occurring during the early phase, accretion onto a neutron star might not be drastically different from accretion onto a black hole because of the trapping of radiation and the effectiveness of neutrino losses close to the neutron star surface (see Chevalier [12]).

Starting from the initial conditions and parameters expected for SN 1987A [12], we have repeated the calculation of Colpi, Shapiro and Wasserman for a spheri-

cally accreting polytropic gas with $\Gamma = 4/3$, including self–gravity. The numerical results are shown in Fig. 2. As can be seen looking at the velocity profile, at the beginning of the evolution (dash–dotted line) three distinct regimes can be recognized: free–fall in the region below the accretion radius r_a, near hydrostatic equilibrium between r_a and the marginally bound radius r_{mb} (below which mass elements are gravitationally bound) and uniform expansion above r_{mb}. At $t \simeq 4700$ s, the accretion rate reaches its maximum value, $\dot{m} \simeq 2 \times 10^{10}$. The late fall back can be described in terms of a dust infall in which only those shells within r_{mb} are eventually accreted [10]. The total accreted mass is $M_{acc} \simeq 0.05 M_\odot$, in agreement with the value estimated by Colpi, Shapiro and Wasserman. Then, although the initial mass contained in the expanding shells is $\sim 5 M_\odot$, only a small fraction is accreted. Since for the Birkhoff theorem the mass outside r_a has no effect on the motion of the inner gas and since M_{acc} is very small in comparison with the mass of the central black hole, self–gravity does not play any important role.

The present simple hydrodynamic model of spherical accretion from a uniformly expanding polytropic gas represents the starting point of this investigation and does not include the transfer of radiation, the role of which might probably become important. In fact, although matter and radiation are presumably in LTE and the efficiency of accretion onto black holes is very low, the actual value of the accretion rate is so high that near Eddington luminosities might be produced, strongly influencing the dynamics of the accretion flow and hence the total accreted mass. This study along with a companion analysis of spherical hypercritical accretion onto neutron stars are presently under way.

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